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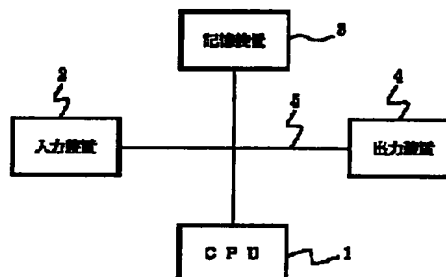
**(54) METHOD AND DEVICE FOR SUPPORTING
DESIGN OF LENS OR THE LIKE**

(57) Abstract:

PURPOSE: To efficiently calculate an optimal design value by properly setting variable difference amount in the design of lens, etc., by the method of attenuation least square.

CONSTITUTION: A CPU 1 calculates the eigen value distribution information on the product matrix ($A^T A$) between the Jacobian matrix A having the variable amount of the characteristic (evaluation function $F_v(X_v)$) of the system for the variable difference amount δx_j of the system being design object as an element and transpose of matrix A^T and sets the variable difference amount δx_j by using the eigen value distribution information. Instead of the eigen value of the product matrix ($A^T A$), the square value of the singular value of the Jacobian matrix A may be used.

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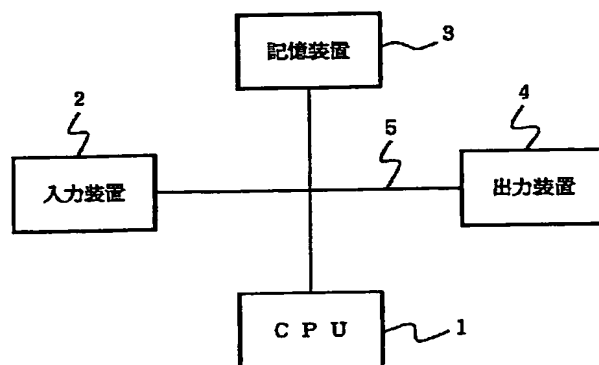
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(54) 【発明の名称】 レンズ等の設計支援装置及び方法

(57) 【要約】

【目的】 減衰最小自乗法によるレンズ等の設計において、変数差分量を適切に設定し、最適な設計値を効率良く算出する。

【構成】 CPU 1は、設計対象となる系の変数差分量 δx_j に対する系の特性 (評価関数 $F_v(X_v)$) の変化量を要素に持つヤコビ行列 A_v とその転置行列 A_v^T との積行列 ($A_v^T A_v$) の固有値分布情報を演算し、その固有値分布情報を用いて変数差分量 δx_j の設定を行う。前記積行列 ($A_v^T A_v$) の固有値に代えて、ヤコビ行列 A の特異値の自乗値を用いてもよい。



の最小値と最大値の間に存在するように前記変数の差分量を設定することを特徴とする請求項 16 記載の設計支援方法。

【請求項 18】 前記ヤコビ行列の特異値の自乗値分布の中央値が減衰最小自乗法におけるダンピングファクタ初期値に略一致するように前記変数の差分量を設定することを特徴とする請求項 16 記載の設計支援方法。

【請求項 19】 前記ヤコビ行列の特異値の自乗値分布の平均値が減衰最小自乗法におけるダンピングファクタ初期値に略一致するように前記変数の差分量を設定することを特徴とする請求項 16 記載の設計支援方法。

【請求項 20】 前記ヤコビ行列の特異値の自乗値分布情報と該自乗値分布に対応して設定された所定の重み付け情報とを用いて前記変数の差分量を設定することを特徴とする請求項 16 記載の設計支援方法。

【発明の詳細な説明】

【0001】

【産業上の利用分野】本発明は、複数の構成要素からなる対象の系が所望の特性となるように、該複数の構成要素を局所的に変更していく最適化手法の内の減衰最小自乗法を用いた設計支援装置及び方法に関し、例えばレンズ設計、LSI の最適パターン設計、建築物の設計などの支援を行うものに関する。

【0002】

【従来の技術】設計の対象となる系を構成する構成要素を n 個の要素から成る変数ベクトル

【0003】

【数 1】

$$X_v = [x_1, \dots, x_n]^T \quad (1)$$

で表わし、該対象の特性を評価する量を m 個の要素から成る評価関数ベクトル

$$A_v = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} & \dots & \frac{\partial F_1}{\partial x_n} \\ \frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} & \dots & \frac{\partial F_2}{\partial x_n} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{\partial F_m}{\partial x_1} & \frac{\partial F_m}{\partial x_2} & \dots & \frac{\partial F_m}{\partial x_n} \end{bmatrix} \quad (6)$$

なお、(6) 式において、 F_i は評価関数ベクトル F_v (X_v) ((2) 式) の第 i 要素 $F_i(X_v)$ を意味する。また、 ΔX_v は変数ベクトルの次のステップへの変動を表わす解ベクトルであり、以下のように表わせる。

【0009】

【数 7】

$$\Delta X_v = [\Delta x_1, \dots, \Delta x_n]^T \quad (7)$$

一般に、減衰最小自乗法では (5) 式をそのまま解く代わりに、2 次微分以上の非線形成分を補正するパラメータ (ダンピングファクタ) ρ を用いて、(8) 式を解

【0004】

【数 2】

$$F_v(X_v) = [F_1(X_v), \dots, F_m(X_v)]^T \quad (2)$$

で表わす。ただし、

【0005】

【数 3】

$$F_k(X_v) = w_k (f_k(X_v) - f_{k,tar}) \quad (3)$$

である。ここで、添字 v は X_v 、 F_v がベクトル (又は行列) であることを示すために付加したものである。また $f_k(X_v)$ 、 $f_{k,tar}$ はそれぞれ各特性値を表わす評価関数の値とその目標値であり、 w_k は重み付け係数である。これらの評価関数には所望の値にすることを目的とした特性値の他、制約条件値を含めてもよい。減衰最小自乗法では、一般に各評価関数値の目標値からのずれ (誤差) 量が最小になるように解が求められ、そのために単一評価尺度として、次式で表わされる目的関数を用いる。

【0006】

【数 4】

$$\Phi(X_v) = F_v^T(X_v) F_v(X_v) \quad (4)$$

(4) 式で与えられる目的関数を特にレンズ設計の分野では、メリット関数と呼び、(4) 式に最小自乗法を適用すると、局所的最小値となるための X_v の必要条件は

【0007】

【数 5】

$$(A_v^T A_v) \Delta X_v = -A_v^T F_v \quad (5)$$

と表わせる。ここで、 A_v は $F_v(X_v)$ のヤコビ (Jacobi) 行列であり、(6) 式で定義される。

【0008】

【数 6】

【数 8】

$$(A_v^T A_v + \rho I_v) \Delta X_v = -A_v^T F_v \quad (8)$$

ここで、 I_v は単位行列を表わす。

【0011】なお、レンズ設計の分野では減衰最小自乗法 (DLS 法: Damped Least Squares method) という名称が広く使われているが、非線形計画法などの分野では、レーベンバーグマーカード (Levenberg-Marquardt) 法という名称が多く用いられている。

【0012】一方、実際の数値計算では、前記 A_v の各要素 a_{ij} は (6) 式で示した様な厳密な微分係数値 (9) 式ではなく差分値 (10) 式を用いて計算され

$$S_v = \begin{bmatrix} s_1 & & 0 \\ & \ddots & \\ 0 & & s_n \end{bmatrix} \quad (12)$$

こうして得られる n 個の固有値 s_1, \dots, s_n の分布は、一般に前述した変数の差分量 δx_j を変化させるに伴って変化する。その際、差分量 δx_j によって直接 n 個の固有値分布を制御するため、本実施例では以下の手法を採用している。

【0028】 先ず、前述した評価関数ベクトル $F_v(X_v)$ の X_{v0} 近傍での線形近似式

【0029】

【数12】

$$F_i(X_v) = F_i(X_{v0}) + A_{vi} \Delta X_v \quad (13)$$

に着目し、評価関数ベクトル $F_v(X_v)$ の第 i 要素を以下のように表わす (14) 式。

【0030】

【数13】

$$A_v' = \begin{bmatrix} \delta_1 F_1 & \delta_2 F_1 & \dots & \delta_n F_1 \\ \delta_1 F_2 & \delta_2 F_2 & \dots & \delta_n F_2 \\ \vdots & \ddots & \ddots & \vdots \\ \delta_1 F_m & \delta_2 F_m & \dots & \delta_n F_m \end{bmatrix} \quad (15)$$

$$\Delta X_v' = \left[\left(\frac{\Delta X_1}{\delta x_1} \right), \dots, \left(\frac{\Delta X_n}{\delta x_n} \right) \right]^T \quad (16)$$

このようにすれば、前記変数の差分量 δx_j により直接前記ヤコビ行列の各要素の値を変化させることができるため、 n 個の固有値の値 $s_1 \sim s_n$ を自由に制御することが可能となる。

【0032】 以上のようにして一旦与えた前記変数の差分量 δx_j による n 個の固有値 $s_1 \sim s_n$ の分布と前記ダンピングファクタ ρ の初期値との関係から、設定された前記変数差分量 δx_j が適切な値であるかどうかを判定するとともに、その情報を用いて、さらに適切な値となるように前記変数差分量 δx_j を変更していくことにより最適な差分量設定を行い、最適な設計値を効率的に得られるようにしている。

【0033】 次に、レンズ設計を例にとりより具体的に説明する。

【0034】 図2は本発明の第1の実施例で設計の対象とした薄肉レンズモデルを示す。図2では見易くするためレンズに厚みを付けてあるが、計算上すべてのレンズ肉厚及び面間隔は0としてある。このレンズ系に対して曲率半径 r_3 を全系の焦点距離が正確に1となるために

$$\begin{aligned} F_i(X_v) &= F_i(X_{v0}) + \left(\frac{\delta F_i}{\delta x_1} \right) \Delta x_1 + \dots + \left(\frac{\delta F_i}{\delta x_n} \right) \Delta x_n \\ &= F_i(X_{v0}) + \delta_1 F_i \left(\frac{\Delta x_1}{\delta x_1} \right) + \dots + \delta_n F_i \left(\frac{\Delta x_n}{\delta x_n} \right) \end{aligned} \quad (14)$$

(14) 式において、 $\delta_j F_i$ は、第 i 評価関数の第 j 変数による変化量を表わす。(14) 式の関係から、ヤコビ行列 A_v (6) 式、及び解ベクトル ΔX_v (7) 式) のかわりにそれぞれ (15) 式、(16) 式のような行列 A_v' 、及びベクトル $\Delta X_v'$ を用いてもまったく同様に最適化演算が行なえることが分かる。

【0031】

【数14】

採用した。初期形状としては、 $(1/r_1, 1/r_2)$ の座標で表わして

$$1/r_1 = -1.8, 1/r_2 = 0.5 \quad (17)$$

とした。そして、これら2つの変数 $(1/r_1)$ 、 $(1/r_2)$ の差分量 $\delta(1/r_1)$ 、 $\delta(1/r_2)$ をそれぞれ

【0035】

【数15】

$$\delta(1/r_1) = 1 \times 10^{-5} \sim 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-5} \sim 1 \times 10^0 \quad (18)$$

なる範囲内で設定する。さらに、設定すべき変数差分量は、(18) 式の範囲で 10^2 ぎざみにすると、各変数について4通り、合計16通りのなかから選べばよいことになる。レンズ設計においては、通常、変数の種別によって、おおよそ設定すべき変数差分量の範囲は経験的に分かっている。

【0036】 この時、各変数差分量設定値における、これら2つの変数及び2つの評価関数に対するヤコビ行列 A_v を求め、積行列 $(A_v^T A_v)$ の2つの固有値 s_1, s_2 を計算すると、以下ようになる (全体を (19) 式と

と、前記 ρ_0 が

【0044】

【数22】

$$s_1 \times 10^{-3} \sim s_1 \times 10^{-2} \leq \rho_0 \leq s_2 \times 10^{-2} \sim s_2 \times 10^0 \quad (26)$$

なる関係を満たすようになっていれば、その時設定された前記変数の差分 $\delta(1/r_1)$ 、 $\delta(1/r_2)$ は適切ということになる。本実施例においては、変数の数が2個であるので、積行列 $(A_V^T A_V)$ の固有値分布の中央値と平均値は一致する。そして前記変数差分量に対応した前記固有値分布の平均値を調べると(25)式のよう設定すれば(26)式の関係が満たされることが分かる。

【0045】上記変数差分量の設定をもっと自動的に行うには、前記固有値 s_1 、 s_2 が ρ 探索範囲に多く含まれるほど評価値が高くなるように、図7に示すような重みづけをすればよい。図7で、横軸が各固有値の値、縦軸がそれぞれの固有値にかかる重みの値であり、固有値が ρ 探索範囲に含まれる場合に1、そうでなければ0となる。

固有値の個数	メリット関数平均値	反復回数平均値
0	0.713	13
1	0.036	10
2	0.034	6.7

この結果から明らかなように ρ 探索範囲に入る固有値の個数が多いものほど、得られるメリット関数値が小さく、反復計算に要した回数も少なくて済む。従って、固有値が ρ 探索範囲に2個入るように変数差分量を設定することにより、効率良く最適な r_1 、 r_2 の設計値を得る。

	メリット関数平均値	反復回数平均値
存在する場合：	0.073	6.6
存在しない場合：	0.143	10.3

この結果から明らかなように、ダンピングファクタ初期値 ρ_0 が固有値分布の最小値と最大値の間に存在するように変数差分量を設定することにより、得られるメリット関数値が小さく反復回数も少なくて済み、最適設計をより効率的に行うことができる。

べき数の差	メリット関数平均値	反復回数平均値
0	0.066	6.6
3	0.005	9.0
4	0.033	13.0
7	0.469	13.0
8	0.958	13.0

この結果から明らかなように、メリット関数値はべき数の差が3程度のとき最小となり、反復回数はべき数の差が小さいほど少ない。従って、べき数の差が2から3程度以内となるように変数差分量を設定することにより、最適設計をより効率的に行うことができる。

【0055】図8は、本発明の第2の実施例の設計対象となるレンズシステムの構成を示す図である。

るように設定されており、これによって評価値がより高くなるような変数差分量を設定すればよい。

【0046】また、ダンピングファクタ初期値 ρ_0 と固有値分布との相対関係に基づいて変数差分量 $\delta(1/r_1)$ 、 $\delta(1/r_2)$ の設定を行う場合には、図8に示すように、ダンピングファクタ初期値 ρ_0 で最も値が高くなり、それから遠ざかるほど徐々に値が低くなるような連続的な重みづけをすれば良い。なお、図7、8に示す重み付け情報(重み付け関数)は記憶装置3に格納されている。

【0047】次に上述した変数差分量の設定により最適化演算を行った場合の結果を説明する。

【0048】まず、 ρ 探索範囲に入る固有値の個数と計算の結果得られたメリット関数平均値、計算に要した反復回数平均値を以下に示す。

【0049】なお、メリット関数値は出発点での値で正規化してある。

【0050】

ことができる。

【0051】次に、ダンピングファクタ初期値 ρ_0 が固有値分布の最小値と最大値の間に存在する場合と存在しない場合についての結果を以下に示す。

【0052】

	反復回数平均値
存在する場合：	6.6
存在しない場合：	10.3

【0053】さらに、ダンピングファクタ初期値 ρ_0 と固有値分布の平均値との差をべき数の差で表わし、差が 10^0 、 10^3 、 10^4 、 10^7 、 10^8 の場合についての結果は以下のようなになる。

【0054】

	メリット関数平均値	反復回数平均値
べき数の差		
0	0.066	6.6
3	0.005	9.0
4	0.033	13.0
7	0.469	13.0
8	0.958	13.0

線収差量を用いた。この合計22個の変数の内訳は面の曲率半径 r が11個と面間隔 g が11個であり、これらの変数差分量を、曲率半径の逆数 $1/r$ に関しては

【0057】

【数23】

$$\delta(1/r) = 1 \times 10^{-5} \sim 1 \times 10^0 \quad (27)$$

面間隔 g に関しては

【0072】次に本発明の第3の実施例においてCPU 1で実行される処理の概要を説明する。

【0073】先ず、前述したヤコビ行列 A_v を以下のように固有値分解する。

【0074】

【数28】

$$P_v = \begin{bmatrix} p_1 & & 0 \\ & \ddots & \\ 0 & & p_n \\ & 0 & \end{bmatrix} \quad (33)$$

$m \leq n$ のとき

【0076】

$$P_v = \begin{bmatrix} p_1 & & 0 \\ & \ddots & \\ 0 & & p_m \\ & & & 0 \end{bmatrix} \quad (34)$$

なる、ヤコビ行列 A_v の n または m 個の特異値を要素に持つ特異値行列である。そして、この特異値行列の積 $P_v^T P_v$ は、

$$P_v^T P_v = \begin{bmatrix} p_1^2 & & 0 \\ & \ddots & \\ 0 & & p_n^2 \end{bmatrix} \quad (35)$$

と表わせる。こうして得られる n 個の特異値の自乗値 p_1^2, \dots, p_n^2 の分布は、一般に前述した変数の差分 δx_j 変化させるに伴って変化する。その際、差分 δx_j によって直接 n 個の特異値の自乗値 p_1^2, \dots, p_n^2 の分布を制御するため、本実施例においても第1の実施例と同様の手法(式(13)～(16))を採用している。これにより、差分 δx_j によって n 個の特異値の自乗値 p_1^2, \dots, p_n^2 を自由に制御することができる。

【0078】以上のようにして一旦与えた前記変数の差分 δx_j による n 個の特異値の自乗値分布と前記ダンピングファクタ ρ の初期値との関係から、設定された変数差分 δx_j が適切な値であるかどうかを判定するとともに、その情報を用いて、さらに適切な値となるように変数差分 δx_j を逐次変更していくことにより最適な差分 δx_j を設定を行い、最適な設計値を効率的に得られるようにしている。

【0079】上述した手法を第1の実施例と同一のレンズシステムに適用し、(19)式に対応するヤコビ行列

$$A_v = U_v P_v V_v^T \quad (32)$$

ここで、 $U_v V_v$ はそれぞれ $m \times m$ 、 $n \times n$ の正規直交行列、 P_v は、 $m > n$ のとき

【0075】

【数29】

【数30】

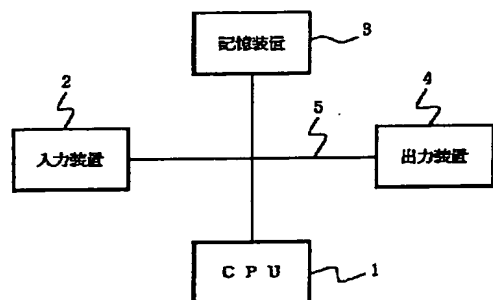
【0077】

【数31】

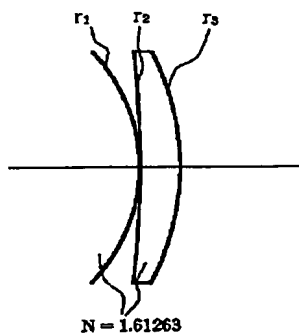
【0080】

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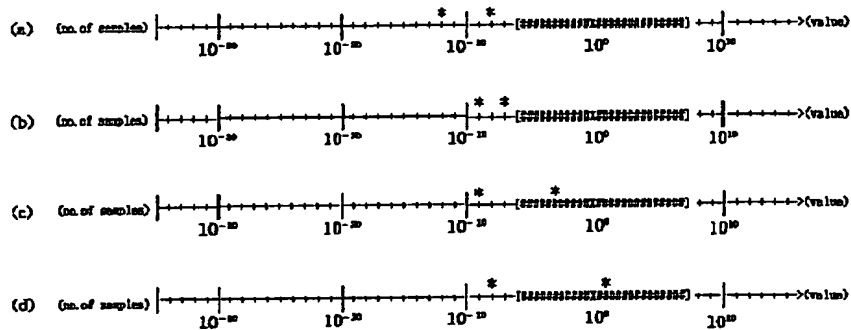
【図 1】



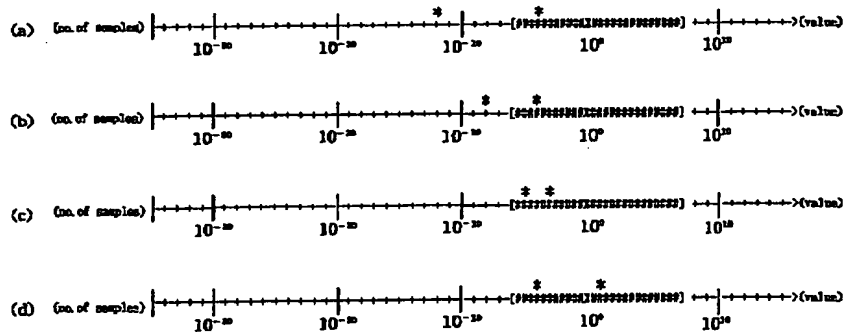
【図 2】



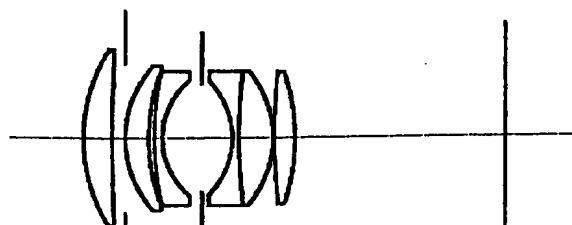
【図 3】



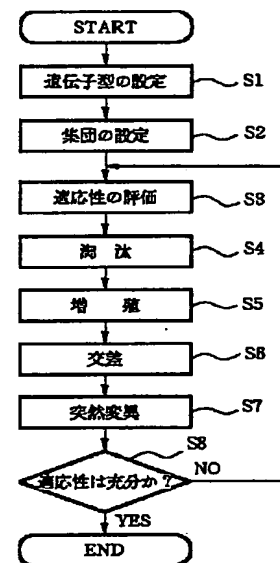
【図 4】



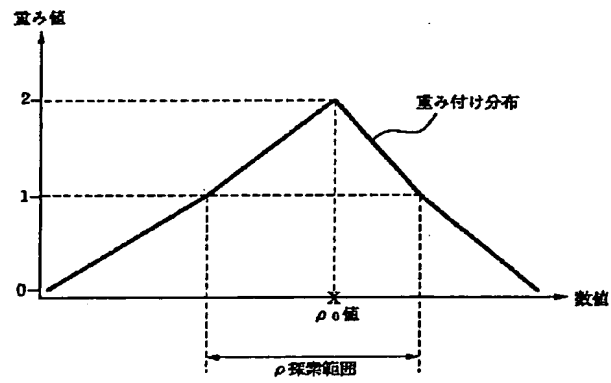
【図 9】



【図 12】



【図10】



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(54) [Title of the Invention] METHOD AND DEVICE FOR
SUPPORTING DESIGN OF LENS OR THE LIKE

(57) [Abstract]

[Object] To efficiently calculate an optimal design value by adequately setting a variable difference amount in the design of a lens or the like by an attenuation least square method.

[Solving Means] A CPU 1 calculates eigen value distribution information on the product matrix ($A_v^T A_v$) of the Jacobian matrix A_v with the variable amount of the characteristic (an evaluation function $F_v(X_v)$) of the system for the variable difference amount δx_j of the system being a design object as elements thereof and the transposed matrix A_v^T and sets the variable difference amount δx_j by using the eigen value distribution information. The square value of

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the singular value of the Jacobian matrix A may be used in place of the eigen value of the product matrix $(A^T A)$.

[Claims]

[Claim 1] A design supporting device to support the design of a lens or the like by an attenuation least square method for locally changing and optimizing a plurality of components so that a system of a design object comprising the plurality of components has a desired characteristic comprising:

an eigen value distribution information operating means to operate eigen value distribution information on the product matrix (Av^TAv) constituted of the product of the Jacobian matrix (Av) with the variable amount of the characteristic of the system to the difference amount of the variables corresponding to the plurality of components as the elements thereof and the transposed matrix (Av^T) of the Jacobian matrix; and

a difference amount setting means to set the difference amount of the variables by using the eigen value distribution information.

[Claim 2] The design supporting device according to Claim 1, wherein the difference amount of the variables is set so that the initial value of the damping factor in the attenuation least square method is present between the minimum value and the maximum value of the eigen value distribution of the product matrix.

[Claim 3] The design supporting device according to Claim 1,

wherein the difference amount of the variables is set so that the median of the eigen value distribution of the product matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 4] The design supporting device according to Claim 1, wherein the difference amount of the variables is set so that the mean of the eigen value distribution of the product matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 5] The design supporting device according to Claim 1, wherein the difference amount of the variables is set by using eigen value distribution information on the product matrix and predetermined weighting information set corresponding to the eigen value distribution.

[Claim 6] A design supporting device to support the design of a lens or the like by an attenuation least square method for locally changing and optimizing a plurality of components so that a system of a design object comprising the plurality of components has a desired characteristic comprising:

a square value distribution information operating means to operate square value distribution information on the eigen value of the Jacobian matrix (A_v) with the variable amount of the characteristic of the system to the difference

amount of the variables corresponding to the plurality of components as the elements thereof; and

a difference amount setting means to set the difference amount of the variables by using the square value distribution information.

[Claim 7] The design supporting device according to Claim 6, wherein the difference amount of the variables is set so that the initial value of the damping factor in the attenuation least square method is present between the minimum value and the maximum value of the square value distribution of the eigen values of the Jacobian matrix.

[Claim 8] The design supporting device according to Claim 6, wherein the difference amount of the variables is set so that the median of the square value distribution of the eigen value of the Jacobian matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 9] The design supporting device according to Claim 6, wherein the difference amount of the variables is set so that the mean of the square value distribution of the eigen value of the Jacobian matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 10] The design supporting device according to Claim 6, wherein the difference amount of the variables is set by

using square value distribution information on the eigen value of the Jacobian matrix and predetermined weighting information set corresponding to the square value distribution.

[Claim 11] A design supporting method to support the design of a lens or the like by an attenuation least square method for locally changing and optimizing a plurality of components so that a system of a design object comprising the plurality of components has a desired characteristic comprising:

a step of operating eigen value distribution information on the product matrix (Av^TAv) constituted of the product of the Jacobian matrix (Av) with the variable amount of the characteristic of the system to the difference amount of the variables corresponding to the plurality of components as the elements thereof and the transposed matrix (Av^T) of the Jacobian matrix; and

a step of setting the difference amount of the variables by using the eigen value distribution information.

[Claim 12] The design supporting method according to Claim 11, wherein the difference amount of the variables is set so that the initial value of the damping factor in the attenuation least square method is present between the minimum value and the maximum value of the eigen value distribution of the product matrix.

[Claim 13] The design supporting method according to Claim 11, wherein the difference amount of the variables is set so that the median of the eigen value distribution of the product matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 14] The design supporting method according to Claim 11, wherein the difference amount of the variables is set so that the mean of the eigen value distribution of the product matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 15] The design supporting method according to Claim 11, wherein the difference amount of the variables is set by using eigen value distribution information on the product matrix and predetermined weighting information set corresponding to the eigen value distribution.

[Claim 16] A design supporting method to support the design of a lens or the like by an attenuation least square method for locally changing and optimizing a plurality of components so that a system of a design object comprising the plurality of components has a desired characteristic comprising:

a step of operating square value distribution information on the eigen value of the Jacobian matrix (Δv) with the variable amount of the characteristic of the system

to the difference amount of the variables corresponding to the plurality of components as the elements thereof; and

a step of setting the difference amount of the variables by using the square value distribution information.

[Claim 17] The design supporting method according to Claim 16, wherein the difference amount of the variables is set so that the initial value of the damping factor in the attenuation least square method is present between the minimum value and the maximum value of the square value distribution of the eigen values of the Jacobian matrix.

[Claim 18] The design supporting method according to Claim 16, wherein the difference amount of the variables is set so that the median of the square value distribution of the eigen value of the Jacobian matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 19] The design supporting method according to Claim 16, wherein the difference amount of the variables is set so that the mean of the square value distribution of the eigen value of the Jacobian matrix is substantially matched with the initial value of the damping factor in the attenuation least square method.

[Claim 20] The design supporting method according to Claim 16, wherein the difference amount of the variables is set by using square value distribution information on the eigen

value of the Jacobian matrix and predetermined weighting information set corresponding to the square value distribution.

Detailed Description of the Invention

[0001]

[Technical Field of the Invention] The present invention relates to a design supporting device and a design supporting method using an attenuation least square method out of optimization methods to locally changing a plurality of components so that an objective system comprising the plurality of components have desired characteristics, and for example, it relates to a design supporting device and a design supporting method to support a lens design, an optimum pattern design of an LSI, a building design and the like.

[0002]

[Description of the Related Art] Components to constitute a system as a design object are expressed by variable vectors consisting of n pieces of elements as follows.

[0003]

[Formula 1]

$$X_v = [X_1, \dots, X_n]^T \quad (1)$$

And the amount to evaluate the characteristics of the object is expressed by an evaluation function vector consisting of m pieces of elements as follows.

[0004]

[Formula 2]

$$F_v(X_v) = [F_1(X_v), \dots, F_n(X_v)]^T \quad (2)$$

[0005]

[Formula 3]

$$F_k(X_v) = w_k\{f_k(X_v) - f_{k,tar}\} \quad (3)$$

Where, suffix v is added to indicate X_v and F_v are vectors (or matrix). Further, $f_k(X_v)$, f_k and tar are the values of the evaluation function to indicate respective characteristic values, and a target value thereof, and w_k is a weighting coefficient. A constraint value may be included in these evaluation functions in addition to the characteristic value intended for a desired value. In the attenuation least square method, a solution is generally obtained so that the amount of deviation (error) from a target value of each evaluation function value is minimized, and an objective function expressed by the following formula is used for a single evaluation scale.

[0006]

[Formula 4]

$$\phi(X_v) = F_v^T(X_v)F_v(X_v) \quad (4)$$

The objective function expressed by the formula (4) is referred to as a merit function in the field of the lens design, in particular. By applying the least square method to the formula (4), the necessary information of X_v for a

local minimum value is given as follows.

[0007]

[Formula 5]

$$(A_v^T A_v) \Delta X_v = -A_v^T F_{v0} \quad (5)$$

Where, A_v is a Jacobian (Jacobi) matrix of $F_v(X_v)$, and defined by Formula (6).

[0008]

[Formula 6]

$$A_v = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} & \dots & \frac{\partial F_1}{\partial x_n} \\ \frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} & \dots & \frac{\partial F_2}{\partial x_n} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{\partial F_m}{\partial x_1} & \frac{\partial F_m}{\partial x_2} & \dots & \frac{\partial F_m}{\partial x_n} \end{bmatrix} \quad (6)$$

In Formula (6), F_i means an i -th element $F_i(X_v)$ of the evaluation function vector $F_v(X_v)$ (Formula (2)). ΔX_v is a solution vector to indicate fluctuation of the variable vector to the next step, and expressed as follows.

[0009]

[Formula 7]

$$\Delta X_v = [\Delta X_1, \dots, \Delta X_n]^T \quad (7)$$

Generally, in the attenuation least square method, an optimum solution is obtained by solving Formula (8) by using a parameter (a damping factor) ρ to correct non-linear components of the secondary or higher differential in place of directly solving Formula (5).

[0010]

[Formula 8]

$$(A_v^T A_v + \rho I_v) \Delta X_v = -A_v^T F_{v0} \quad (8)$$

Where, I_v is a unit matrix.

[0011] In the field of the lens design, a term of the attenuation least square method (DLS method: a Damped Least Squares method) is extensively used. On the other hand, in the field of the non-linear planning method or the like, a term of the Levenberg-Marquardt method is extensively used.

[0012] On the other hand, in the actual numerical calculation, each element a_{ij} of A_v is calculated not by using a strict differential coefficient value (Formula (9)) expressed by Formula (6), but calculated by using Formula (10) for the difference value.

[0013]

[Formula 9]

$$a_{ij} = \partial F_1 / \partial x_j \quad (9)$$

$$a_{ij} = \delta F_1 / \delta x_j \quad (10)$$

[0014]

[Problems to be Solved by the Invention] However, the value of the optimum variable difference amount δx_j is diversified according to the characteristic of the object system, raising a problem in that, if an inadequate value is given, errors occur in the numerical computation, many iterative calculations are required, and the optimum solution cannot be efficiently obtained.

[0015] The present invention is achieved in light of this point, and an object of the present invention is to provide a design supporting device and a design supporting method capable of obtaining the optimum solution in a constantly efficient manner by adequately setting the variable difference amount.

[0016]

[Means for Solving the Problems] In order to achieve the above-described object of the present invention, a design supporting device to support the design of a lens or the like by an attenuation least square method for locally changing and optimizing a plurality of components so that a system of a design object comprising the plurality of components has a desired characteristic comprises an eigen value distribution information operating means to operate eigen value distribution information on the product matrix $(Av^T Av)$ constituted of the product of the Jacobian matrix (Av) with the variable amount of the characteristic of a system to the difference amount of the variables corresponding to the plurality of components as the elements thereof and the transposed matrix (Av^T) of the Jacobian matrix, and a difference amount setting means to set the difference amount of the variables by using the eigen value distribution information.

[0017] In order to achieve the same object of the present

invention, in a design supporting method to support the design of a lens or the like by an attenuation least square method for locally changing and optimizing a plurality of components so that a system of a design object comprising the plurality of components has a desired characteristic, eigen value distribution information is operated on the product matrix ($Av^T Av$) constituted of the product of the Jacobian matrix (Av) with the variable amount of the characteristic of the system to the difference amount of the variables corresponding to the plurality of components as the elements thereof and the transposed matrix (Av^T) of the Jacobian matrix, and the difference amount of the variables is set by using the eigen value distribution information.

[0018] Further, preferably in the design supporting device or the design supporting method, the difference amount of the variables is set so that the initial value of the damping factor in the attenuation least square method is present between the minimum value and the maximum value of the eigen value distribution of the product matrix, the difference amount of the variables is set so that the median of the eigen value distribution of the product matrix is substantially matched with the initial value of the damping factor in the attenuation least square method, the difference amount of the variables is set so that the mean of the eigen value distribution of the product matrix is

substantially matched with the initial value of the damping factor in the attenuation least square method, and the difference amount of the variables is set by using eigen value distribution information on the product matrix and predetermined weighting information set corresponding to the eigen value distribution.

[0019] In addition, in the design supporting device or the design supporting method, the "square value distribution of the singular values of the Jacobian matrix (A_v)" may be used in place of the "eigen value distribution of the product matrix ($A_v^T A_v$)".

[0020]

[Operation] According to the device of Claim 1 or according to the method of Claim 11, eigen value distribution information on the product matrix ($A_v^T A_v$) of the Jacobian matrix (A_v) with the variable amount of the characteristic of the system to the difference amount of the variables corresponding to a plurality of components as the elements thereof and the transposed matrix (A_v^T) of the Jacobian matrix, and the difference amount of the variables is set by using the eigen value distribution information.

[0021] According to the device of Claim 6 or according to the method of Claim 16, square value distribution information on the singular values of the Jacobian matrix (A_v) with the variable amount of the characteristic of the

system to the difference amount of the variables corresponding to a plurality of components as the elements thereof is operated, and the difference amount of the variables is set by using the square value distribution information.

[0022]

[Embodiments] Embodiments of the present invention will be described with reference to the drawings.

[0023] Fig. 1 shows a configuration of a design supporting device according to an embodiment of the present invention. This device comprises a CPU (a Central Processing Unit) 1 to perform various kinds of operations to optimize a variable corresponding to a component of a system for the design object, an input device 2 to input data and operation commands to the CPU 1 by a user, a storage device 3 to store programs executed by the CPU 1 and data or the like under operations, and an output device 4 to display the result of operations on a display device or to print the result of operations by a printer. These components 1 to 4 are connected to each other by a bus 5.

[0024] Next, the outline of the processing executed by the CPU 1 will be described.

[0025] Firstly, the product matrix $(Av^T Av)$ of the above-described Jacobian matrix Av and a transposed matrix Av^T thereof is subjected to the eigen value break-down as

follows.

[0026]

[Formula 10]

$$(A_v^T A_v) = V_v S_v V_v^T \quad (11)$$

Where, V_v denotes an orthogonal matrix, and S_v denotes an diagonal matrix of n , n -type with n -eigen values of the product matrix $(A_v^T A_v)$ as elements as shown in Formula (12).

[0027]

[Formula 11]

$$S_v = \begin{bmatrix} s_1 & & 0 \\ & \ddots & \\ 0 & & s_n \end{bmatrix} \quad (12)$$

The distribution of n - eigen values s_1, \dots, s_n which are thus obtained is generally changed as the difference amount δx_j of the above-described variable is changed. In this case, the following method is employed in the present embodiment to directly control n -eigen value distribution by the difference amount δx_j .

[0028] Firstly, attention is paid to a linear approximation in a vicinity of X_{v0} of the above-described evaluation function vector $F_v(X_v)$ as expressed below.

[0029]

[Formula 12]

$$F_v(X_v) = F_v(X_{v0}) + A_v \Delta X_v \quad (13)$$

Then, the i -th element of the evaluation function

vector $Fv(Xv)$ will be expressed as follows (Formula (14)).

[0030]

[Formula 13]

$$\begin{aligned} F_i(X_v) &= F_i(X_0) + \left(\frac{\partial F_i}{\partial x_1}\right) \Delta x_1 + \cdots + \left(\frac{\partial F_i}{\partial x_n}\right) \Delta x_n \\ &= F_i(X_0) + \delta_i F_i \left(\frac{\Delta x_1}{\delta x_1}\right) + \cdots + \delta_n F_i \left(\frac{\Delta x_n}{\delta x_n}\right) \quad (14) \end{aligned}$$

In Formula (14), $\delta_j F_i$ denotes the variable amount by the i -th variable of the i -th evaluation function. From the relationship of Formula (14), it is proved that completely similar optimum operation can be performed even by using the matrix Av' and the vector $\Delta Xv'$ such as in Formulae (15) and (16) in place of the Jacobian matrix Av (Formula (6)) and the solution vector ΔXv (Formula (7)).

[0031]

[Formula 14]

$$Av' = \begin{bmatrix} \delta_1 F_1 & \delta_2 F_1 & \cdots & \delta_n F_1 \\ \delta_1 F_2 & \delta_2 F_2 & \cdots & \delta_n F_2 \\ \vdots & \ddots & \ddots & \vdots \\ \delta_1 F_m & \delta_2 F_m & \cdots & \delta_n F_m \end{bmatrix} \quad (15)$$

$$\Delta Xv' = \left[\left(\frac{\Delta x_1}{\delta x_1} \right), \cdots, \left(\frac{\Delta x_n}{\delta x_n} \right) \right]^T \quad (16)$$

By this method, the value of each element of the Jacobian matrix can be directly changed by the difference amount δx_j of the variable, and n -eigen values of s_1 to s_n can be freely controlled.

[0032] As described above, it is determined whether or not the set variable difference amount δx_j is an adequate value from the relationship between distribution of n -eigen values s_1 to s_n by the difference amount δx_j of the variable which is once given and the initial value of the damping factor ρ , and the optimum difference amount is set by changing the variable difference amount δx_j so as to obtain a more adequate value by using the information, and the optimal design value is efficiently obtained.

[0033] Next, the present invention will be described more specifically by an example of the lens design.

[0034] Fig. 2 shows a thin-walled lens model as the design object according to the first embodiment of the present invention. In Fig. 2, the lens has a thickness so as to easily show the embodiment. However, the lens thickness and the spacing in the calculation are set to be zero. The radius of curvature r_3 is used so that the focal distance of the entire system is correctly 1 to this lens system, and remaining two radii of curvature r_1 and r_2 are defined as variables. The tertiary spherical difference coefficient and the coma aberration coefficient are employed as two evaluation functions. The initial shape is expressed by the coordinates of $(1/r_1, 1/r_2)$ as follows.

$$1/r_1 = -1.8, \text{ and } 1/r_2 = 0.5 \quad (17)$$

The difference amounts $\delta(1/r_1)$ and $\delta(1/r_2)$ of these two

variables $(1/r_1)$ and $(1/r_2)$ are set in a range specified as follows.

[0035]

[Formula 15]

$$\delta(1/r_1) = 1 \times 10^{-6} \sim 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-6} \sim 1 \times 10^0 \quad (18)$$

In addition, the variable difference amount to be set may be selected from four cases for each variable, i.e., sixteen in total at every 10^2 in the range of Formula (18). Generally, in the lens design, the range of the variable difference amount to be roughly set is empirically understood according to the kind of the variables.

[0036] In this condition, the Jacobian matrix Av for two variables and two evaluation functions in each variable difference amount set value is obtained. Two eigen values s_1 and s_2 of the product matrix $(Av^T Av)$ are calculated as follows (entirely expressed by Formula (19)).

(Margin below)

[0037]

[Formula 16]

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-6}$$

$$s_1 = 8.6 \times 10^{-13}, s_2 = 2.2 \times 10^{-8} \text{ (Fig. 3(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-4}$$

$$s_1 = 8.0 \times 10^{-10}, s_2 = 2.3 \times 10^{-7} \text{ (Fig. 3(b))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-2}$$

$$s_1 = 9.0 \times 10^{-10}, s_2 = 2.1 \times 10^{-3} \text{ (Fig. 3(c))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^0$$

$$s_1 = 5.5 \times 10^{-9}, s_2 = 6.8 \times 10^0 \text{ (Fig. 3(d))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-6}$$

$$s_1 = 8.6 \times 10^{-13}, s_2 = 2.2 \times 10^{-4} \text{ (Fig. 4(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-4}$$

$$s_1 = 8.6 \times 10^{-9}, s_2 = 2.2 \times 10^{-4} \text{ (Fig. 4(b))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-2}$$

$$s_1 = 8.2 \times 10^{-6}, s_2 = 2.3 \times 10^{-3} \text{ (Fig. 4(c))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^0$$

$$s_1 = 5.5 \times 10^{-6}, s_2 = 6.8 \times 10^0 \text{ (Fig. 4(d))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-6}$$

$$s_1 = 8.6 \times 10^{-13}, s_2 = 2.2 \times 10^0 \text{ (Fig. 5(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-4}$$

$$s_1 = 8.6 \times 10^{-9}, s_2 = 2.2 \times 10^0 \text{ (Fig. 5(b))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-2}$$

$$s_1 = 2.2 \times 10^0, s_2 = 8.7 \times 10^{-5} \text{ (Fig. 5(c))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^0$$

$$s_1 = 4.3 \times 10^{-1}, s_2 = 8.5 \times 10^0 \text{ (Fig. 5(d))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-6}$$

$$s_1 = 5.8 \times 10^{-13}, s_2 = 5.2 \times 10^{+3} \text{ (Fig. 6(a))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-4}$$

$$s_1 = 5.8 \times 10^{-9}, s_2 = 5.2 \times 10^{+3} \text{ (Fig. 6(b))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-2}$$

$$s_1 = 5.9 \times 10^{-6}, s_2 = 5.2 \times 10^{+3} \text{ (Fig. 6(c))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^0$$

$$s_1 = 1.5 \times 10^0, s_2 = 5.2 \times 10^{+3} \text{ (Fig. 6(d))}$$

(19)

As described above, the eigen value distribution of each product matrix (Av^TAv) is indicated in Fig. 3(a) to Fig. 6(d). These figures indicate the eigen value distribution operated by the CPU 1 and printed by the output device 4. In each figure, the numerals are exponentially indicated on the horizontal axis, and the position of each eigen value (s_1, s_2) is indicated by *. Further, the position of the initial value ρ_0 of the damping factor ρ is indicated by X on the horizontal axis, and the search range of the damping factor ρ therearound (hereinafter, referred to as " ρ search range") is indicated by [## ... ##]. In the present embodiment, ρ_0 is set as follows.

$$\rho_0 = 1.0 \quad (20)$$

In addition, the ρ search range is set as follows.

[0038]

[Formula 17]

$$\rho_0 \times 10^{-6} \sim \rho_0 \times 0.5 \times 10^8 \quad (21)$$

In the present invention, an adequate value of the difference amount of the variable is set from eigen value distribution information on the product matrix (Av^TAv), and it is empirically understood in the field of the lens design to set one including the eigen values s_1 and s_2 in the ρ search range as many as possible. In this case, as clearly

shown in Figs. 3 to 6, one including no eigen values s_1 and s_2 in the ρ search range is a case shown below (Formula (22)).

[0039]

[Formula 18]

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-6} \text{ (Fig. 3(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-4} \text{ (Fig. 3(b))}$$

(22)

Further, one including one eigen value (s_1 or s_2) is the case shown below (Formula (23)).

[0040]

[Formula 19]

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-2} \text{ (Fig. 3(c))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^0 \text{ (Fig. 3(d))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-6} \text{ (Fig. 4(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-4} \text{ (Fig. 4(b))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-6} \text{ (Fig. 5(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-4} \text{ (Fig. 5(b))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-6} \text{ (Fig. 6(a))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-4} \text{ (Fig. 6(b))}$$

(23)

Further, one including both the eigen values s_1 and s_2 is the case shown below (Formula (24)).

[0041]

[Formula 20]

$$\begin{aligned}
 \delta(1/r_1) &= 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-2} \text{ (Fig. 4(c))} \\
 \delta(1/r_1) &= 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^0 \text{ (Fig. 4(d))} \\
 \delta(1/r_1) &= 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-2} \text{ (Fig. 5(c))} \\
 \delta(1/r_1) &= 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^0 \text{ (Fig. 5(d))} \\
 \delta(1/r_1) &= 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-2} \text{ (Fig. 6(c))} \\
 \delta(1/r_1) &= 1 \times 10^0, \delta(1/r_2) = 1 \times 10^0 \text{ (Fig. 6(d))}
 \end{aligned}
 \tag{24}$$

By setting any one of the variable difference amounts shown in Formula (24), iterative calculation to search the value of the damping factor ρ can be efficiently performed on the average. In order to set an adequate value of the variable difference amount more clearly, one in which the initial value ρ_0 of the damping factor ρ is smaller than the maximum value and larger than the minimum value of the eigen value distribution of the product matrix (Av^TAv) .

[0042]

[Formula 21]

$$\begin{aligned}
 \delta(1/r_1) &= 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^0 \text{ (Fig. 3(d))} \\
 \delta(1/r_1) &= 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^0 \text{ (Fig. 4(d))} \\
 \delta(1/r_1) &= 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-6} \text{ (Fig. 5(a))} \\
 \delta(1/r_1) &= 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-4} \text{ (Fig. 5(b))} \\
 \delta(1/r_1) &= 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^0 \text{ (Fig. 6(c))}
 \end{aligned}
 \tag{25}$$

In the present embodiment, this requirement is satisfied.

[0043] In addition, an adequate value of the variable difference amount is quantitatively set, one may be set, in which the initial value of the damping factor corresponding to a plurality of variables r_1 and r_2 is substantially matched with the median or the mean of the eigen value distribution of the product matrix (Av^TAv) . Substantial matching is different by the object, and it is empirically understood that matching by 10^2 to 10^3 is sufficient for the case of the lens design. In other words, when the median or the mean of the eigen value distribution of the product matrix (Av^TAv) is expressed by s_m , the difference amount $\delta(1/r_1)$ and $\delta(1/r_2)$ of the variable set at that time if ρ_0 satisfies the relationship shown below.

[0044]

[Formula 22]

$$s_m \times 10^{-3} \sim s_m \times 10^{-2} \leq \rho_0 \leq s_m \times 10^2 \sim s_m \times 10^3 \quad (26)$$

In the present embodiment, there are two variables, and the median and the mean of the eigen value distribution of the product matrix (Av^TAv) are matched with each other. When checking the mean of the eigen value distribution corresponding to the variable difference amount, it is proved that the relationship of Formula (26) is satisfied if being set like Formula (25).

[0045] To set the variable difference amount more automatically, weighting as shown in Fig. 7 may be performed

so that the evaluation value becomes higher as more eigen values s_1 and s_2 are included in the ρ search range. In Fig. 7, the value on the horizontal axis indicates each eigen value, and the value on the vertical axis indicates the weight on each eigen value. If the eigen value is included in the ρ search range, 1 is set, otherwise 0 is set. The variable difference amount may be set so that the evaluation value is much higher thereby.

[0046] Further, if the variable difference amounts $\delta(1/r_1)$ and $\delta(1/r_2)$ are set based on the relationship between the initial value ρ_0 of the damping factor and the eigen value distribution, continuous weighting may be performed so that the value becomes maximum at the initial value ρ_0 of the damping factor shown in Fig. 8, and the value is gradually decreased as being farther therefrom. In addition, weighting information (the weighting function) shown in Figs. 7 and 8 is stored in the storage device 3.

[0047] The result of the optimum operation by setting the above-described variable difference amount will be described below.

[0048] Firstly, the number of the eigen values in the ρ search range, the mean of the merit function obtained by the result of calculation, and the mean of the iteration number required in the calculation will be indicated below.

[0049] The merit function value is normalized by the value

at the starting point.

[0050]

Number of eigen value	Mean of merit function	Mean of iteration number
0	0.713	13
1	0.036	10
2	0.034	6.7

As clearly shown from this result, the more the number of the eigen values included in the ρ search range is, the smaller the obtained merit function value is, and the smaller the iteration number is required. Therefore, the design values of the optimum r_1 and r_2 can be obtained by setting the variable difference amount so that two eigen values are included in the ρ search range.

[0051] Next, the result will be shown below for the case in which the initial value ρ_0 of the damping factor is present between the minimum value and the maximum value of the eigen value distribution and the case in which the initial value ρ_0 of the damping factor is not present therebetween.

[0052]

	Mean of merit function	Mean of iteration number
Present:	0.073	6.6
Not present:	0.143	10.3

As clearly shown from this result, by setting the variable difference amount so that the initial value ρ_0 of the damping factor is present between the minimum value and the maximum value of the eigen value distribution, the obtained merit function value becomes small, and the iteration number also becomes small, and the optimal design can be efficiently performed.

[0053] In addition, the result will be shown below for the case in which the difference between the initial value ρ_0 of the damping factor and the mean of the eigen value distribution is expressed by the exponent difference, and the difference is 10^0 , 10^3 , 10^4 , 10^7 and 10^8 , respectively.

[0054]

Exponent difference	Mean of merit function	Mean of iteration number
0	0.066	6.6
3	0.005	9.0
4	0.033	13.0
7	0.469	13.0
8	0.958	13.0

As clearly shown from this result, the merit function value is minimized when the exponent difference is about 3, and the iteration number becomes less as the exponent difference is smaller. Therefore, the optimal design can be efficiently performed by setting the variable difference amount so that the exponent difference is within a range of 2 and 3.

[0055] Fig. 8 shows a configuration of a lens system as a design object according to the second embodiment of the present invention.

[0056] In the present embodiment, twenty two variables consisting of lens components are used, and the beam aberration is mainly used for the evaluation function to indicate the characteristic of the lens. The break-down of these twenty-two variables includes eleven surface radii r of curvature, and eleven kinds of spacing g , and the variable difference amounts are set to an optimum value in terms of the inverse $1/r$ of the radius of curvature in a range as follows.

[0057]

[Formula 23]

$$\delta(1/r) = 1 \times 10^{-6} \sim 1 \times 10^0 \quad (27)$$

The variable difference amounts are set to an optimum value in terms of the spacing g in a range as follows.

[0058]

[Formula 24]

$$\delta(g) = 1 \times 10^{-3} \sim 1 \times 10^0 \quad (28)$$

When each variable difference amount is considered at the interval of 10^1 , all possible combinations will be given as follows.

[0059]

[Formula 25]

$$7^{11} \times 4^{11} \approx 8.3 \times 10^{15} \text{ cases}$$

Even if all these combinations are checked in 10^{-6} second per combination, it would take an immense amount of time of about 263 years. This is one of the most difficult problems (a so-called NP-completion type problem) to obtain a strict solution in the combination-optimization problem. A genetic algorithm (Genetic Algorithm) has been extensively known as a method to efficiently solve the approximate solution of this kind of problem. The genetic algorithm was devised by J. H. Holland in 1960s, and this is a method for efficiently solving an optimization problem by simulating the essence of the biological evolution as it is on the computer.

[0060] More specifically, this method is executed by the procedure as shown in Fig. 12. Firstly, in Step S1, the problem is modeled, and the gene type is set. For example, a numerical string (10100110) is used for the gene type.

Next, a large number of individuals of different genes (numerical strings in this case) are formed (for example, 10110001, 01101010, 11101100 ...) (Step S2). And, the adaptability of the formed individuals is evaluated (Step S3). In other words, each individual (series) is evaluated by using the predetermined evaluation function, and the individuals (series) of low evaluation will be selected in Step S4.

[0061] In Step S5, the not-selected individuals are multiplied to compensate the number of selected individuals, and the crossing-over (Step S6) and the mutation (Step S7) are performed. If the adaptability of the obtained individuals is insufficient, Steps S3 to S7 will be repeated. Here, the crossing-over is performed by switching specified parts by selecting specified gene pairs, and the mutation is performed by changing some parts of the gene at some probability.

[0062] When the above-described processing is applied to the setting of the optimum variable difference amount, a point is how the gene type is set and how the adaptability is evaluated.

[0063] In the present embodiment, firstly, the series in which an arbitrary pair of difference amount set values are expressed by the exponent are employed. In other words, the first to eleventh number of the series from the left to the

right are set as the exponent value of the difference amount on each radius r of curvature, the twelfth to twenty-second number of the series are set to be the exponent value of the difference amount on each spacing g , all the difference amounts of $1/r$ are set to be 1×10^{-6} , and all the difference amounts of g are set to be 1×10^{-6} , the gene row to indicate this state is expressed as follows.

$$-6-6-6-6-6-6-6-6-6-6-6-3-3-3-3-3-3-3-3-3-3-3-3 \quad (29)$$

[0064] On the other hand, information on the eigen value distribution of the product matrix ($A^T A$) is used for the evaluation of the adaptability. More specifically, the result of higher evaluation will be obtained when the initial value ρ_0 of the damping factor is smaller than the maximum of the eigen values of the product matrix ($A^T A$), and larger than the minimum thereof.

[0065] When the adaptability is evaluated more strictly, the initial value ρ_0 is compared with the median or the mean of the eigen value distribution, and higher evaluation will be obtained when the initial value is substantially matched with the median or the mean of the eigen value distribution.

[0066] In the present embodiment, weighting of the distribution as shown in Fig. 10 is performed, and the evaluation value becomes higher when the eigen value is not outside the ρ search range but within the range, and higher evaluation is obtained when the eigen value is close to the

initial value ρ_0 of the damping factor though it is within the ρ search range.

[0067] Description will be given by a specifically numerical example. Firstly, in the variable difference amount, the radius r of curvature and the spacing g of the plane are set to be common as follows.

[0068]

[Formula 26]

$$\begin{aligned}\delta(1/r) &= 1 \times 10^{-6} \\ \delta(g) &= 1 \times 10^{-3} \quad (30)\end{aligned}$$

In this condition, the eigen value distribution is examined as shown in Fig. 11(a). This state forms a starting point, and the weighting distribution in Fig. 10 is multiplied by the eigen value distribution in Fig. 11(a) to obtain the evaluation value, and processing is performed to set an adequate variable difference amount by the genetic algorithm. The variable difference amount set value obtained as the result is as shown below for the radius r of curvature and the spacing g , respectively.

[0069]

[Formula 27]

$$\begin{aligned}\delta(1/r) &= 1 \times 10^{-5} \sim 1 \times 10^{-2} \\ \delta(g) &= 1 \times 10^{-3} \sim 1 \times 10^{-1} \quad (31)\end{aligned}$$

The eigen value distribution corresponding to the variable difference amount set value (31) is shown in Fig.

11(b). As clearly shown from the comparison between Fig. 11(a) and Fig. 11(b), it is shown that the eigen value distribution is gathered around the initial value ρ_0 of the damping factor $\rho_0 (= 1.0)$ by the above-described processing.

[0070] Comparison of the normalized merit function value and the iteration number required for the calculation before and after the above-described processing is as follows.

[0071]

	Merit function value	Iteration number of calculation
Before processing	5.0×10^{-3}	3
After processing	1.3×10^{-3}	3

As clearly shown from this result, according to the present embodiment, the convergence efficiency of the attenuation least square method can be enhanced.

[0072] Next, the outline of the processing executed by the CPU 1 in the third embodiment of the present invention will be described.

[0073] Firstly, the Jacobian matrix A_v is subjected to the eigen value break-down.

[0074]

[Formula 28]

$$A_v = U_v P_v V_v^T \quad (32)$$

Where, $U_v V_v$ denote orthonormal matrixes of m, m type

and n , n type, respectively, and when $m > n$, P_v is expressed as follows.

[0075]

[Formula 29]

$$P_v = \begin{bmatrix} p_1 & & & 0 \\ & \ddots & & \\ 0 & & & p_n \\ & 0 & & \end{bmatrix} \quad (33)$$

When $m \leq n$, P_v is expressed as follows.

[0076]

[Formula 30]

$$P_v = \begin{bmatrix} p_1 & & 0 \\ & \ddots & \\ 0 & & p_m \\ & & & 0 \end{bmatrix} \quad (34)$$

P_v is a singular value matrix with n - or m - singular values of the Jacobian matrix A_v as the elements thereof. The product $P_v^T P_v$ of the singular value matrix is expressed as follows.

[0077]

[Formula 31]

$$P_v^T P_v = \begin{bmatrix} p_1^2 & & 0 \\ & \ddots & \\ 0 & & p_n^2 \end{bmatrix} \quad (35)$$

The distribution of the square values p_1^2, \dots, p_n^2 of the thus-obtained n - singular values is changed by the difference amount δx_j of the above-described variables. In

this condition, in order to directly control the distribution of the square values p_1^2, \dots, p_n^2 of the thus-obtained n - singular values by the difference amount δx_j , a method (Formulae (13) to (16)) similar to that of the first embodiment is employed also in the present embodiment. Therefore, the square values p_1^2, \dots, p_n^2 of the thus-obtained n - singular values can be freely controlled by the difference amount δx_j .

[0078] As described above, it is determined whether or not the set variable difference amount is adequate from the relationship of the square value distribution of the distribution of n - singular values of the once-given variables by the difference amount δx_j and the initial value of the damping factor ρ , and optimum difference amount is set by successively changing the variable difference amount δx_j so as to obtain a further adequate value by using the information so that the optimal design value is efficiently obtained.

[0079] The above-described method is applied to the same lens system identical to that of the first embodiment, and the square values p_1^2 and k_2^2 of the singular values of the Jacobian matrix A_v corresponding to Formula (19) are calculated as follows (the entire values are expressed by Formula (36)).

[0080]

[Formula 32]

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-6}$$

$$p_1^2 = 8.6 \times 10^{-13}, p_2^2 = 2.2 \times 10^{-8} \text{ (Fig. 3(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-4}$$

$$p_1^2 = 8.0 \times 10^{-10}, p_2^2 = 2.3 \times 10^{-7} \text{ (Fig. 3(b))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^{-2}$$

$$p_1^2 = 9.0 \times 10^{-10}, p_2^2 = 2.1 \times 10^{-8} \text{ (Fig. 3(c))}$$

$$\delta(1/r_1) = 1 \times 10^{-6}, \delta(1/r_2) = 1 \times 10^0$$

$$p_1^2 = 5.5 \times 10^{-9}, p_2^2 = 6.8 \times 10^0 \text{ (Fig. 3(d))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-6}$$

$$p_1^2 = 8.6 \times 10^{-13}, p_2^2 = 2.2 \times 10^{-4} \text{ (Fig. 4(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-4}$$

$$p_1^2 = 8.6 \times 10^{-9}, p_2^2 = 2.2 \times 10^{-4} \text{ (Fig. 4(b))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^{-2}$$

$$p_1^2 = 8.2 \times 10^{-6}, p_2^2 = 2.3 \times 10^{-3} \text{ (Fig. 4(c))}$$

$$\delta(1/r_1) = 1 \times 10^{-4}, \delta(1/r_2) = 1 \times 10^0$$

$$p_1^2 = 5.5 \times 10^{-6}, p_2^2 = 6.8 \times 10^0 \text{ (Fig. 4(d))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-6}$$

$$p_1^2 = 8.6 \times 10^{-13}, p_2^2 = 2.2 \times 10^0 \text{ (Fig. 5(a))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-4}$$

$$p_1^2 = 8.6 \times 10^{-9}, p_2^2 = 2.2 \times 10^0 \text{ (Fig. 5(b))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^{-2}$$

$$p_1^2 = 2.2 \times 10^0, p_2^2 = 8.7 \times 10^{-5} \text{ (Fig. 5(c))}$$

$$\delta(1/r_1) = 1 \times 10^{-2}, \delta(1/r_2) = 1 \times 10^0$$

$$p_1^2 = 4.3 \times 10^{-1}, p_2^2 = 8.5 \times 10^0 \text{ (Fig. 5(d))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-6}$$

$$p_1^2 = 5.8 \times 10^{-13}, p_2^2 = 5.2 \times 10^{+3} \text{ (Fig. 6(a))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-4}$$

$$p_1^2 = 5.8 \times 10^{-9}, p_2^2 = 5.2 \times 10^{+3} \text{ (Fig. 6(b))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^{-2}$$

$$p_1^2 = 5.9 \times 10^{-6}, p_2^2 = 5.2 \times 10^{+3} \text{ (Fig. 6(c))}$$

$$\delta(1/r_1) = 1 \times 10^0, \delta(1/r_2) = 1 \times 10^0$$

$$p_1^2 = 1.5 \times 10^0, p_2^2 = 5.2 \times 10^{+3} \text{ (Fig. 6(d))}$$

(36)

As clearly shown above, the distribution of the square values of the singular values of the Jacobian matrix Av is totally same as the distribution of the eigen values of the product matrix $(Av^T Av)$. In other words, the square values p_1^2 and p_2^2 of the singular values of the Jacobian matrix Av are equal to the eigen values of the product matrix $(Av^T Av)$. [0081] Therefore, in the first embodiment, replacement of the singular values of the eigen values s_1 and s_2 of the product matrix $(Av^T Av)$ by the square values p_1^2 and p_2^2 corresponds to the present embodiment, and similar effect to the first embodiment can also be demonstrated by the present embodiment.

[0082] Further, similar replacement can also be performed even in the second embodiment.

[0083]

[Advantages] As described above in detail, according to the

design supporting device of Claim 1, or according to the design supporting method of Claim 11, eigen value distribution information on the product matrix ($Av^T Av$) constituted of the product of the Jacobian matrix (Av) with the variable amount of the characteristic of the system to the difference amount of the variables corresponding to a plurality of components as the elements thereof and the transposed matrix (Av^T) of the Jacobian matrix is operated, and the difference amount of the variables is set by using the eigen value distribution information. Therefore, the optimum value by the descent method is efficiently operated, and the optimal design value can be efficiently obtained.

[0084] Further, according to the design supporting device of Claim 6 or according to the design supporting method of Claim 16, square value distribution information on the singular values of the Jacobian matrix (Av) with the variable amount of the characteristic of the system to the difference amount of the variables corresponding to a plurality of components as the elements thereof, and the difference amount of the variables is set by using the square value distribution information, and similar effect can be demonstrated thereby.

[Brief Description of the Drawings]

[Fig. 1] Fig. 1 shows a configuration of a design supporting device according to an embodiment of the present

invention.

[Fig. 2] Fig. 2 shows a configuration of a first lens system as a design object.

[Fig. 3] Fig. 3 shows distribution of the eigen value (a square value of a singular value of a Jacobian matrix) of a product matrix of the Jacobian matrix and a transposed matrix thereof.

[Fig. 4] Fig. 4 shows distribution of the eigen value (a square value of a singular value of a Jacobian matrix) of a product matrix of the Jacobian matrix and a transposed matrix thereof.

[Fig. 5] Fig. 5 shows distribution of the eigen value (a square value of a singular value of a Jacobian matrix) of a product matrix of the Jacobian matrix and a transposed matrix thereof.

[Fig. 6] Fig. 6 shows distribution of the eigen value (a square value of a singular value of a Jacobian matrix) a product matrix of the Jacobian matrix and a transposed matrix thereof.

[Fig. 7] Fig. 7 shows an example of weighting information (a weighting function).

[Fig. 8] Fig. 8 shows an example of weighting information (a weighting function).

[Fig. 9] Fig. 9 shows a configuration of a second lens system as a design object.

[Fig. 10] Fig. 10 shows an example of weighting information (a weighting function).

[Fig. 11] Fig. 11 shows distribution of the eigen value (a square value of a singular value of a Jacobian matrix) a product matrix of the Jacobian matrix and a transposed matrix thereof.

[Fig. 12] Fig. 12 shows a flowchart to indicate the procedure of a genetic algorithm.

[Reference Numerals]

- 1 CPU
- 2 input device
- 3 storage device
- 4 output device

FIG. 1

- 2 INPUT DEVICE
- 3 STORAGE DEVICE
- 4 OUTPUT DEVICE

FIG. 7

- 1 WEIGHTING VALUE
- 2 WEIGHTING DISTRIBUTION
- 3 NUMERICAL VALUE
- 4 ρ_0 VALUE
- 5 ρ SEARCH RANGE

FIG. 8

- 1 WEIGHTING VALUE
- 2 WEIGHTING DISTRIBUTION
- 3 NUMERICAL VALUE
- 4 ρ SEARCH RANGE

FIG. 10

- 1 WEIGHTING VALUE
- 2 WEIGHTING DISTRIBUTION

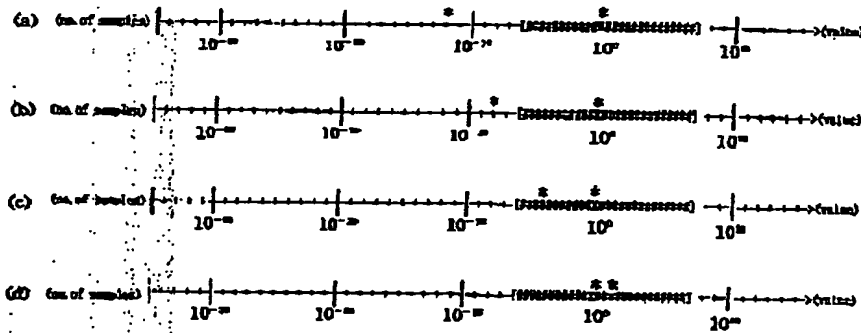
- 3 NUMERICAL VALUE
- 4 ρ_0 VALUE
- 5 ρ SEARCH RANGE

FIG. 12

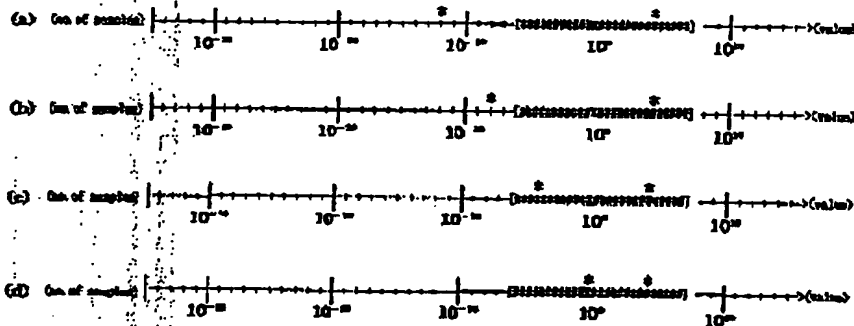
- S1 SET GENE TYPE
- S2 SET GROUP
- S3 EVALUATE ADAPTABILITY
- S4 SELECTION
- S5 MULTIPLICATION
- S6 CROSSING-OVER
- S7 MUTATION
- S8 IS ADAPTABILITY SUFFICIENT?

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【図5】

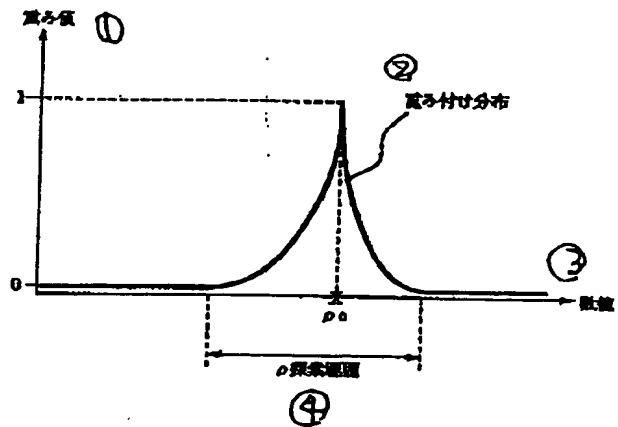
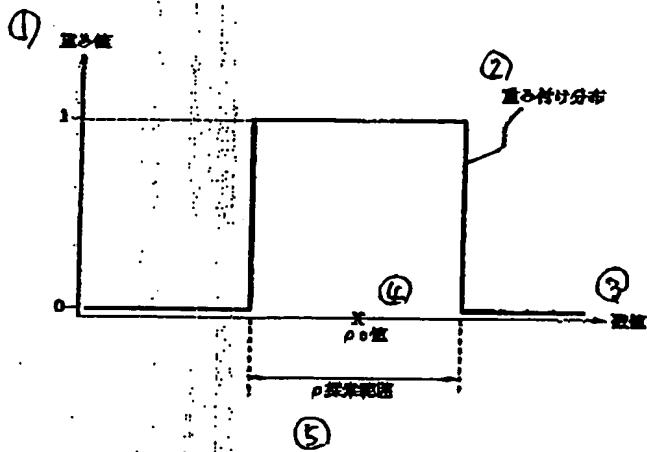


【図6】



【図7】

【図8】



【図11】



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【図10】

